

Role of a Single Shield in Thermocouple Measurements in Hot Air Flow

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To investigate the role of a single shield on steady temperature measurement using thermocouples in hot air flow, a methodology for solving convection, conduction, and radiation in one single model is provided. In order to compare with the experimental results, a cylindrical computational domain is established, which is the same size with the hot calibration wind-tunnel. In the computational domain, two kinds of thermocouples, the bare-bead and the single-shielded thermocouples, are simulated respectively. Surface temperature distribution and the temperature measurement bias of the two typical thermocouples are compared. The simulation results indicate that: 1) The existence of the shield reduces bead surface heat flux and changes the direction of wires inner heat conduction in a colder surrounding; 2) The existence of the shield reduces the temperature measurement bias both by improving bead surface temperature and by reducing surface temperature gradient; 3) The shield effectively reduces the effect of the ambient temperature on the temperature measurement bias; 4) The shield effectively reduces the influence of airflow velocity on the temperature measurement bias.

Keywords: single-shield, bare-bead thermocouples, temperature measurement, fluid-solid conjugated heat transfer.

Introduction

Thermocouples have been widely used to measure air-flow total temperature in research and industry. Bare-bead thermocouples, with the advantages of convenience, low cost, robustness and fast response time, are probably the most common, and possibly the easiest to implement. However, the uncertainty associated with this measurement method may be enormous[1]. One main reason for the measurement uncertainty is radiative exchange between the bead junction and the surrounding environment[2-4]. This is the consequence of bare-bead thermocouples directly exposing to the measurement environment.

In order to reduce the measurement error of bare-bead

thermocouples due to radiative exchange, single-shielded thermocouples are increasingly used in many applications. A single-shielded thermocouple has a cylindrical tube enclosed in a bare-bead thermocouple. The gas to be measured enters shield from the shield entrance, exchanges heat with the thermocouple bead and then flows out along the shield exit.

In the past few decades, a significant amount of works has investigated the uncertainty of temperature measurement using bare-bead and single-shielded thermocouples. Blevins et al. developed a steady-state energy balance model to study the measurement error associated with bare-bead, single and double shielded aspirated thermocouple measurements[5, 6]. The model provides a methodology to study the thermocouple measurement

Nomenclature

d_b	bead diameter(mm)	D_w	domain inlet diameter(mm)
d_w	wire diameter(mm)	T_s	static temperature (K)
L_w	bare wire length(mm)	V_b	bead volume(m ³)

d_{s1}	shell outer diameter(mm)	Greek letters	
d_{s2}	shield outer diameter(mm)	Γ	Recovery factor
d_e	shield entrance diameter(mm)	θ	Relative temperature deviation
d_v	shield vent diameter(mm)	Subscripts	
T_b	bead temperature(K)	<i>cond</i>	conduction
T_w	wall temperature(K)	<i>conv</i>	convection
Q	rate of heat transfer(W)	<i>rad</i>	radiation

error trend. Luo [7] compared the difference of the reading from a bare-bead thermocouple with that from a suction pyrometer in a series of fire experiments. The results show that the reading from the bare-bead thermocouple could be more than 200°C higher than that from the suction pyrometer. Brohez et al [8] performed the experiments using a two thermocouples probe for the radiation corrections of measured temperature. A two thermocouples probe of unequal diameters was proposed to correct the thermocouple readings.

As reviewed above, most scholars have made experimental studies or algebraic analysis on thermocouples measurement, the global performance and total errors of thermocouples have been obtained. However, there are very few studies available regarding three dimensional modeling of a thermocouple. Compared with these two methods, a three-dimensional numerical study is capable of accounting for the deviation and delivering the local air flow temperatures and velocities at any desired positions in the field. Kim and Hamins [9] developed a three-dimensional simplified model to evaluate the measurement bias focusing on double shielded aspirated thermocouples. After compared with algebraic solutions, the measurement uncertainty characterized with the indicated thermocouple temperature and surrounding temperature was given. Etemad [10] performed a three-dimensional numerical study on the bare-bead model without considering the conduction. The bare-bead thermocouple is simplified as a small solid spherical bead. The results show that radiation is responsible for the temperature difference which grows with both bead size and gas temperature but decreases with the Reynolds number.

In this paper, to study the role of shield in thermocouples high temperature measurements, a detailed numerical approach with consideration of realistic boundary condition is described. Unlike early 3-D thermocouple numerical models introduced many simplifications, the model used in this investigation take all the main components of thermocouples into consideration. Therefore, a combined solution of the flow field, energy equations, conduction in the thermocouple and radiation between different surfaces is obtained in these simulations. The numerical method is confirmed by experimental results. The thermocouple temperature measurement bias is characterized with the surrounding temperature and airflow Mach number. The effect of shield on temperature distribution and temperature measurement bias are discussed. Hopefully the present study gives a better understanding about the difference of measurement bias caused by heat transferring between the bare-bead thermocouples and the single-shielded thermocouples.

Numerical Scheme

A thermocouple calibration in a hot calibration wind tunnel has been done before this numerical study. The computational result is compared with the experimental data to validate the numerical method. The further investigations in the role of single shield in the hot airflow temperature measurement will be discussed then.

The computational domain and grid description

The K-type bare-bead thermocouple model, illustrated in Fig.1, consists of a bare bead, dual-wire, and a probe shell while the single-shielded thermocouple is identical to the bare-bead thermocouple enclosed in a radiation shield as shown in Fig.2.

The bead (d_b) and wires (d_w) have diameters of 1.5mm and 0.5mm respectively while the exposed wire length (L_w) is specified to 8 mm. The shield has a 6mm outer diameter (d_{s2}) and 1mm wall thickness, which is the same as the shell (d_{s1}). The shield entrance (d_e) and vent (d_v) diameters are 4 mm and 2 mm respectively and the shield entrance-to-vent area ratio is 4.

The computational domain is composed of a geometry same as the test section of the hot calibration wind-tunnel and a hybrid grid is used in the domain, which are shown in Fig.3. The domain inlet diameter is 2000 times of the bead diameter. The bead of thermocouple model is located in the axial line of the computational domain. The distance between thermocouple bead center and the inlet is one time the wind-tunnel diameter, while the distance between thermocouple bead center and the outlet is two times.

Unstructured grid is employed in the region surrounding the probe, and the O-type grid is used for the other

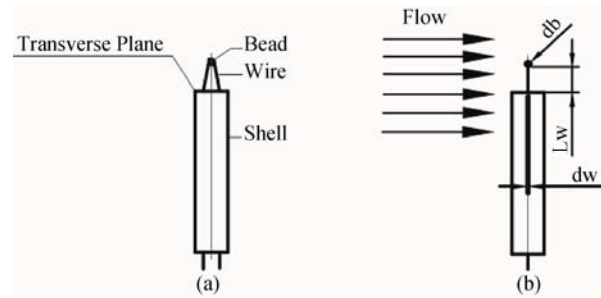


Fig. 1 Schematic of the bare dual-wire thermocouple (not to scale). The arrows are drawn to indicate the flow direction.

regions. Meanwhile, the size function [11] is applied to ensure the well stitching between the structured grid and unstructured grid. The y^+ values remain about 1 which met the enhanced wall function. In all cases, the grid skewness and aspect ratios are kept within reasonable bounds.

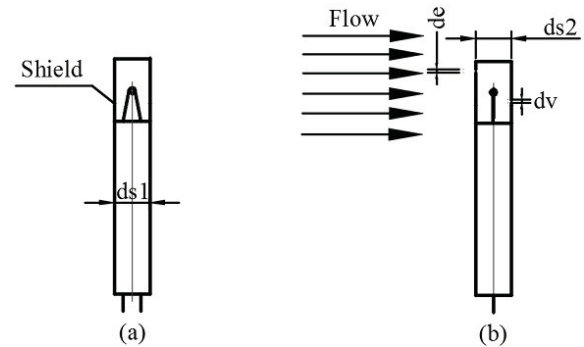
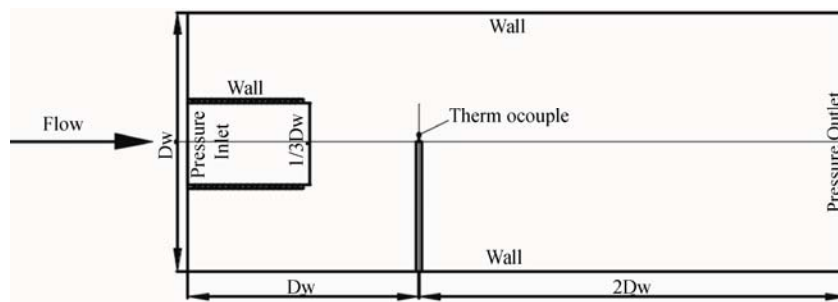
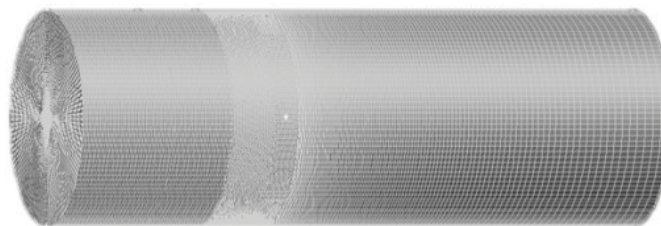


Fig. 2 Schematic of the single-shielded thermocouple (not to scale). The arrows are drawn to indicate the flow direction.



(a)



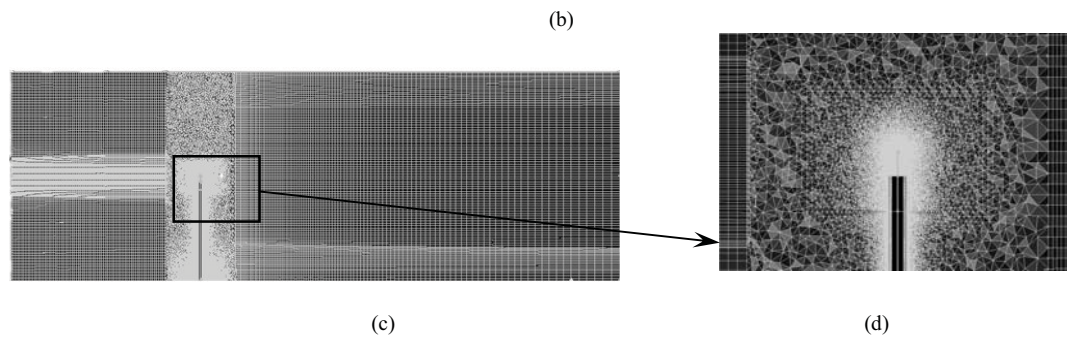


Fig. 3 The illustration of the computational domain and mesh. a) The computational domain. b) The mesh of the entire domain outer surface. c) The mesh of the entire domain intersecting surface. d) The refined grid in the near bead region.

The boundary condition and turbulence model

At the inlet of the computational domain, a total temperature of 1073 K and a total pressure are specified, which are acquired from the experiment. The atmospheric pressure is applied to the outlet. No-slip temperature condition is applied as the boundary condition for the wind-tunnel wall. This temperature is obtained at different positions of the wind-tunnel wall, and then is averaged due to the little temperature discrepancy. In all cases, an emissivity of 0.3 is used for the solid wall except for 0.8 for the dual-wire and bead surfaces, as described in reference[12].

The turbulence model used is realizable k- ϵ with enhanced wall treatment in the near wall region, the Discrete Ordinate model is employed to solve the radiative heat transfer equation. The SIMPLEC algorithm is used to generate solutions. All equations are integrated over each cell of the grid system. The fluxes at the cell faces are interpolated by using the second-order upwind scheme.

The fluid at the inlet is specified as ideal gas mixture which is assumed to be ideal fluid with a density variation dependent on the temperature only. The composition of the fluid is also acquired from the experiment. All other physical properties of ideal gas mixture are modified and kept unchanged for each temperature. The thermocouple model is K type and its physical properties are considered as constant for this work as well.

The convergence criterion is met when the residuals reach 10^{-4} . All calculations are performed by using FLUENT.

Numerical method verification

The experiments are conducted in a hot calibration wind-tunnel. The total temperature is recorded by a double-shield suction thermocouple which is mounted at the same transverse plane with the calibrated thermocouple to obtain a more actual temperature. And Mach number is confirmed by the pressure sensors. When the temperature and velocity of gas reached steady-state, the corresponding parameters are recorded.

The grid independence is verified by computing the thermocouple in the hot calibration wind tunnel on four grids. The numbers of grid points are 4×10^6 cells, 6×10^6 cells, 7.5×10^6 and 9×10^6 cells. All the grids are refined near the wall. Fig.4 shows the variation of relative temperature deviation, θ ($(T_t - T_b)/T_t$), with the grid numbers. Based on the verification, all the data presented later were obtained with the grid (7.5×10^6). T_b is thermocouple indicative temperature and T_t is the gas total temperature. The first grid point away from the refined region has a y^+ value less than 1 and the first five grid points have y^+ less than 5.

Temperature measurements are undertaken at different Mach numbers. Fig.5 illustrates that the numerical results of the bare-bead thermocouple shows the same trend with the

experimental results and the calculated temperature ratio have a good agreement with the experimental values at different Mach numbers. T_b represents the volume average temperature of the bead while T_t indicates the total temperature. Thus, this numerical simulation is a feasible approach to study the temperature measurements using the thermocouples.

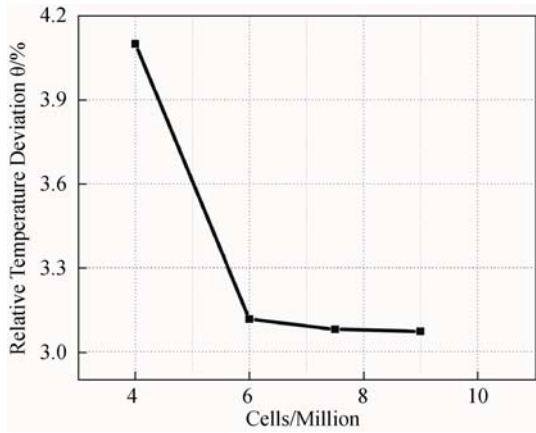


Fig. 4 Relative temperature deviation (θ) versus grid numbers

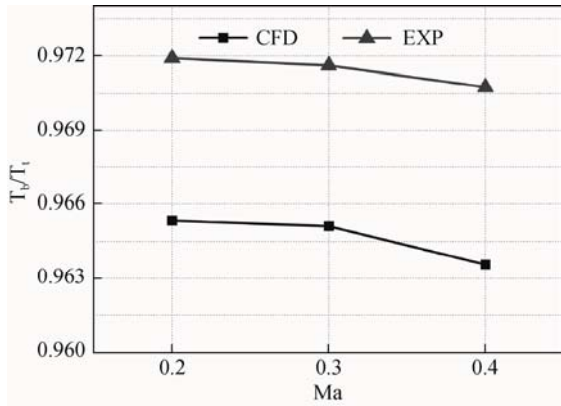


Fig. 5 Temperature ratio (T_b/T_t) of bare thermocouple versus Ma

The fluid is set to air after the model was validated for simplifying the question. The simulated cases are listed as Table 1.

Table 1 List of simulated cases

Variables	Values
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T_w (K)	293, 1000
T_t (K)	1073
Ma	0.1, 0.3, 0.5

Results

Schematic diagram of different slices used for auxiliary explanation is shown in Fig.6.

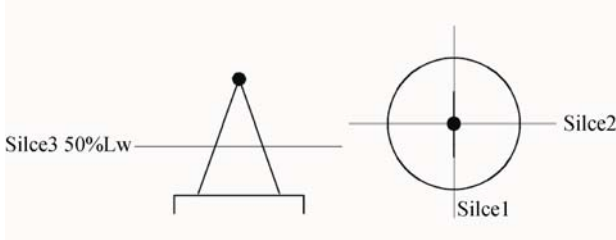


Fig. 6 Schematic diagram of different slices.

Effect of shield on heat flux on the wires and bead surfaces

Heat is transferred to or from the bead via convection and radiation on surface and via conduction along the wires. Surface heat transfer rate was calculated by using an area integral as follows:

$$Q = \int q \, dA = \sum q_i \, dA_i \quad (1)$$

To calculate heat conduction of bead along the wire, the formula of the energy balance on the bead is established as follows:

$$Q_{convection} = Q_{radiation} + Q_{conduction} \quad (2)$$

Therefore, heat conduction flux could be calculated as:

$$Q_{conduction} = Q_{convection} - Q_{radiation} \quad (3)$$

The shield significantly reduces surface heat exchange and changes the influence of conduction on the measurement when radiant heat transfer is relatively intense.

From Fig.7.a), the shield reduces the radiative exchange between the thermocouple and the surrounding, especially in a colder surrounding. When the computational domain wall temperature is 293K, the net radiative heat exchange between the single-shielded thermocouple and the surrounding is nearly

15% of that between the bare-bead thermocouple and the surrounding. The existence of shield makes the bead surface radiative exchange heat flux with the shield inner wall mainly, whose temperature is higher than that of the computational domain wall. This leads to a reduction in the radiative exchange in steady state.

From Fig.7.b), the shield reduces the convective heat exchange between the thermocouple and the flow especially when the computational domain wall temperature is low. Fig.9 shows the flow field of two types of thermocouples near in the bead region when airflow total temperature is 1073K, the computational domain wall temperature is 293K and the Mach number is 0.3. It shows that shield transformed the flow direction near the bead. Compared to airflow directly impacts the bare-bead thermocouple surface, the shield reduces the airflow velocity and reduces the difference of airflow velocity along the wire axial direction as well. This leads to a reduction in convective heat transfer coefficient in steady state.

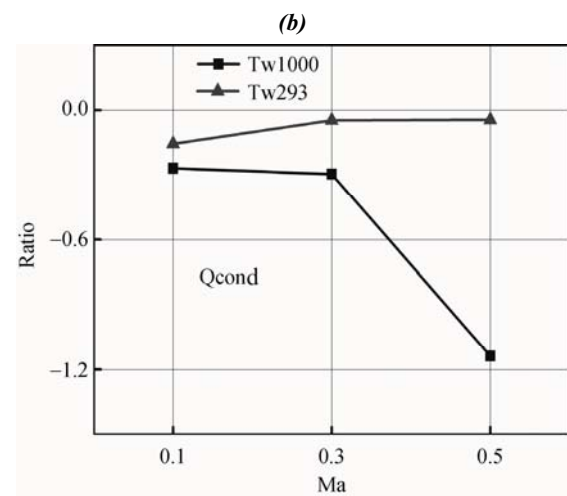
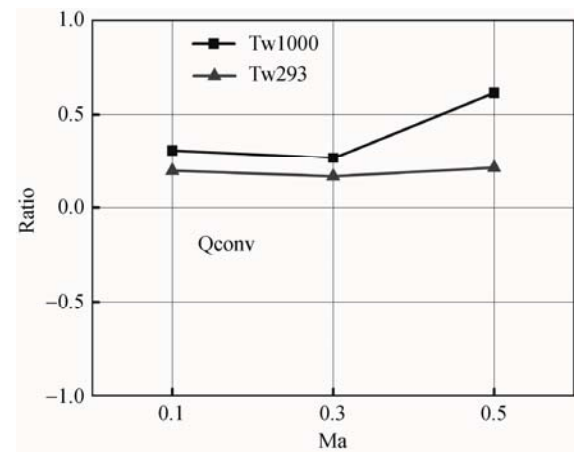
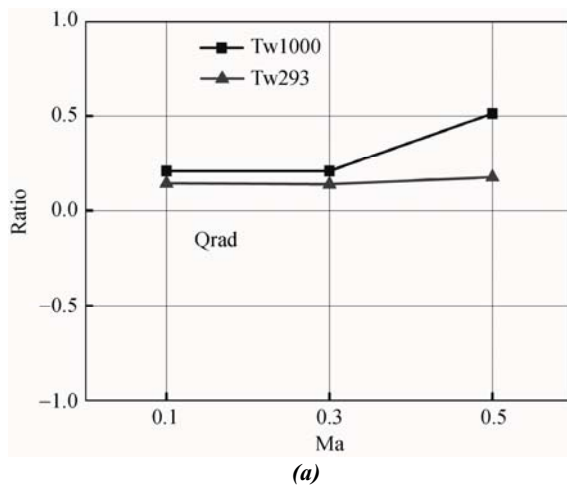


Fig. 7 Heat transfer ratio of the single-shielded thermocouples to the bare-bead thermocouples: a) radiative heat transfer; b) convective heat transfer; c) conductive heat transfer.

From Fig.7.c), the shield changes the direction of heat conduction along wire when the wall temperature is 293K as the conductive heat transfer ratio of the single-shielded thermocouples to the bare-bead thermocouples is negative.

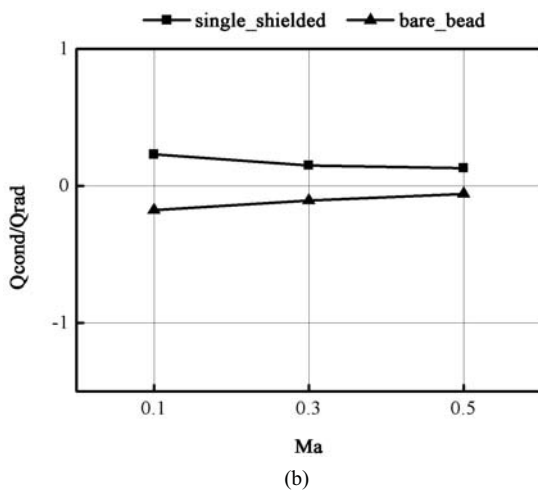
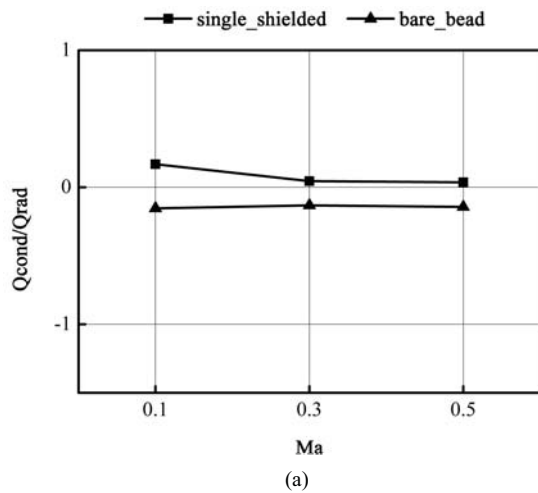


Fig. 8 The ratio of conduction heat transfer to radiation heat transfer: a) $T_w = 293\text{ K}$; b) $T_w = 1000\text{ K}$.

From Fig.8.b), the absolute value of the ratio of conduction heat transfer to radiation heat transfer is bigger in single-shielded thermocouple when the wall temperature is 1000 K. A conclusion can be obtained that the shield increases the influence of conduction on the measurement when the wall temperature is high.

From Fig.8, the ratio of conduction heat transfer to radiation heat transfer of two types in all simulated cases is nearly 0.1. Therefore, the influence of conduction on the measurement is relatively small.

Effect of shield on temperature distribution on the wire and bead surface

Since this study mostly focused on the difference of

surface temperature distribution between the bare-bead and the single-shielded thermocouples in the near-bead region, it is chosen to show sample results in the near bead region, detailed results for the entire domain are not presented. Fig.10,12,13 show the results for the cases with a Mach number of 0.3, an airflow total temperature of 1073 K and a wall temperature of 293 K.

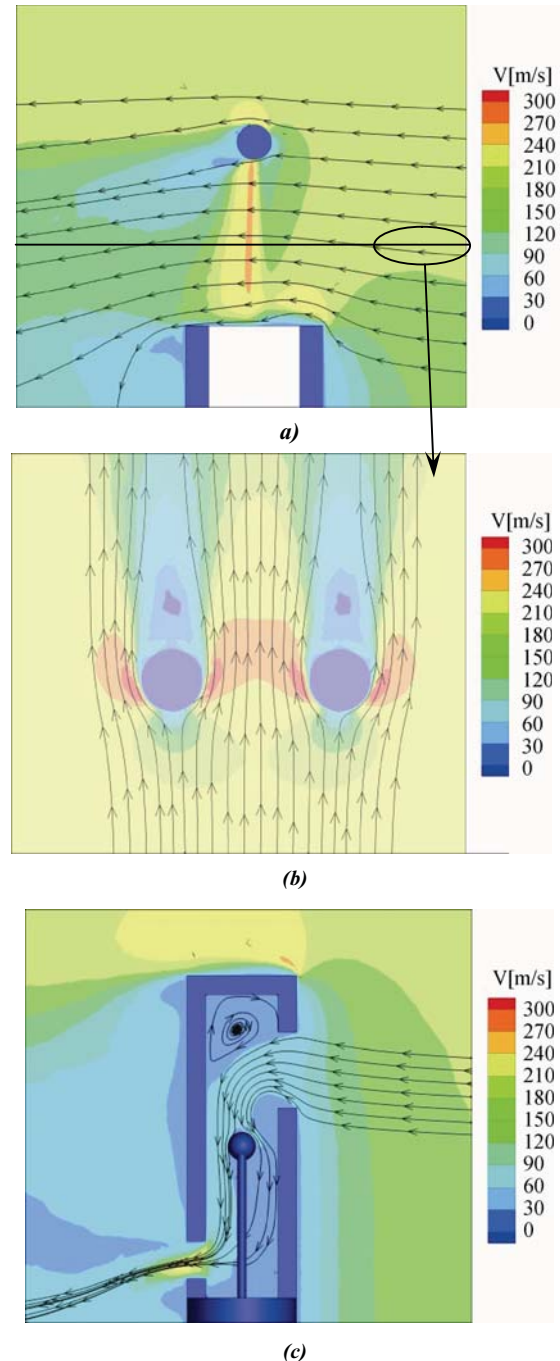


Fig. 9 The flow field of two types of thermocouples near the bead region: a) slice2 of the bare-bead thermocouple; b) slice 3 of the bare-bead thermocouple; c) slice 2 of the single-shielded thermocouple

The shield dramatically improved the bead surface temperature as compared to a bare-bead thermocouple for an airflow total temperature of 1073 K. From Fig.10, a nearly 25 K closer to the airflow total temperature is found when comparing the single-shielded thermocouple bead surface average temperature with the bare-bead one.

What's more, the bead surface temperature gradient is smaller as the existence of single-shield. Fig.11 shows the maximum surface temperature deviation of two typical thermocouples changed with different Mach numbers. It can be seen from Fig.11 that as the Mach number increases, the bead surface temperature differences of the bare-bead thermocouple increase. The difference could be around 10 K at high Mach number. However, the maximum surface temperature differences

of the single-shielded thermocouple, maintained at about 0.3 K, do not substantially change with increasing Mach number.

In summary, the use of single-shield can be expected to reduce the temperature measurement bias both by improving the bead surface temperature and by reducing surface temperature gradient.

Fig.12.b) and Fig.13.b) show the inner temperature distribution of two types of thermocouples bead. The inner temperature distribution has the same trend of surface temperature distribution. Fig.15 shows the wire surface average temperature along wire axial direction. It could be seen that the single-shielded thermocouple wire surface average temperature decreases from bead to thermocouple wire roots. However, for the bare-bead thermocouple, there is a high temperature core area in the wire central surface. The surface temperature increases firstly and then decreases. Therefore, the existence of shield changes the direction of wire inner heat conduction when the wall temperature is low.

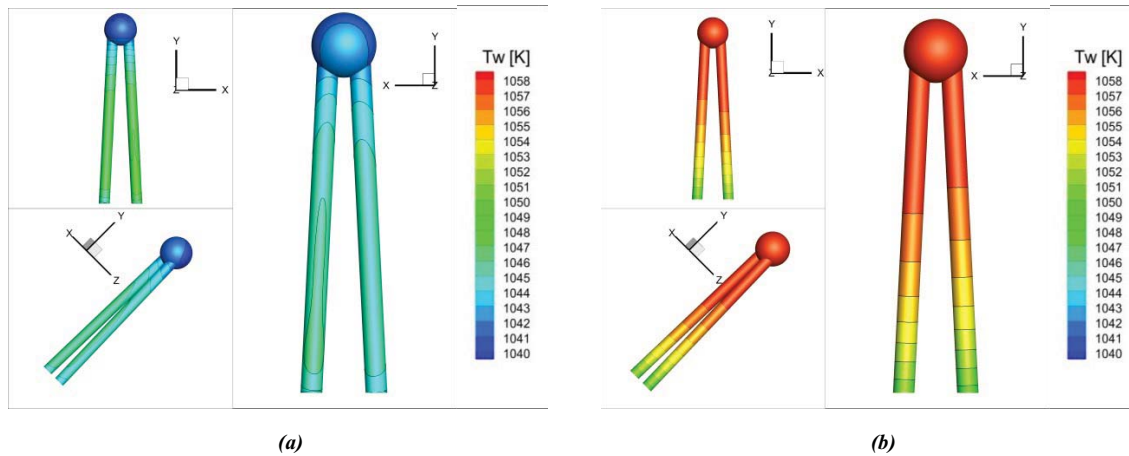


Fig. 10 Temperature distribution on the wire and bead surface: (a) the bare-bead thermocouples, (b) the single-shielded thermocouples(The positive direction of Z-axis is the inflow direction.).

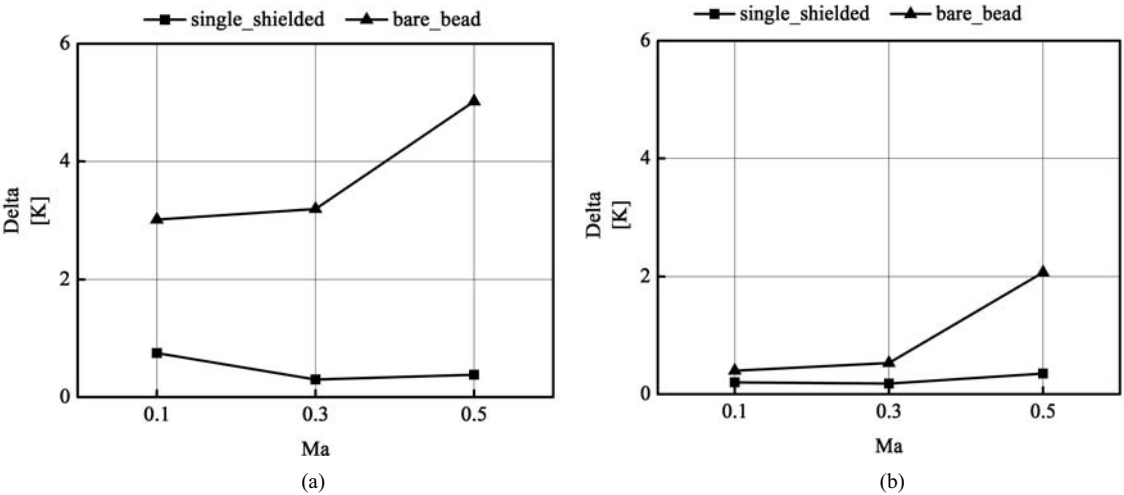


Fig. 11 The maximum surface temperature deviation of two types of thermocouples versus different Mach numbers. The airflow total temperature is 1073 K.a) the computational domain wall temperature is 293 K, b) the computational domain wall temperature is 1073 K.

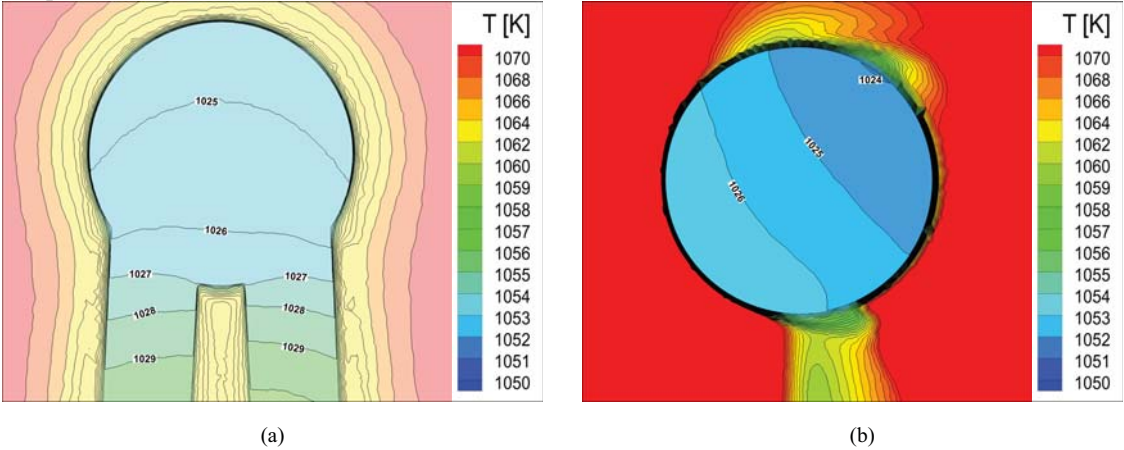


Fig. 12 Temperature contours of the bare-bead thermocouple case: (a) slice1. (b) slice2.

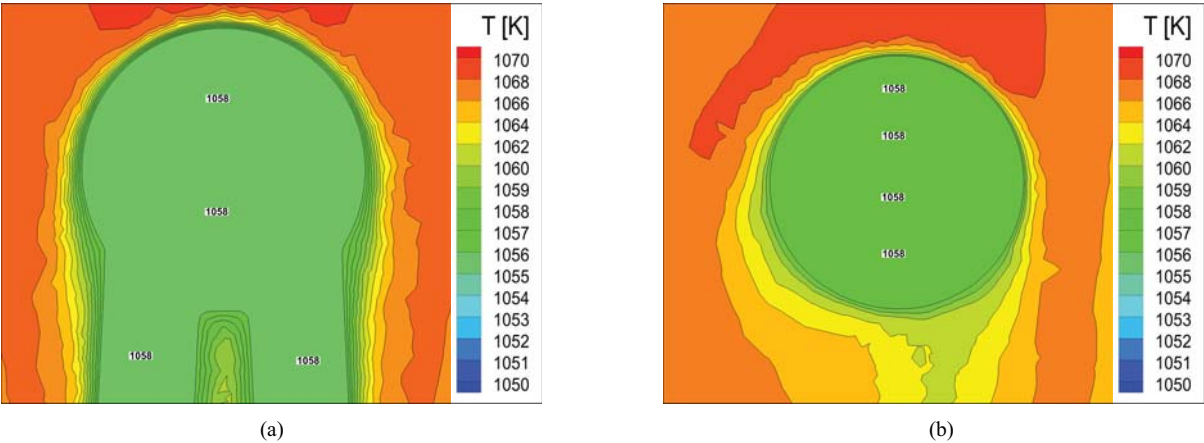


Fig. 13 Temperature contours of the single-shielded thermocouple case: (a) slice1. (b) slice2.

Fig.14 shows the surface circumferential temperature distribution of thermocouple wires

central section. It could be seen from Fig.14 that the shield makes surface temperature distribution at wire circumferential direction more even. The shield decreases the difference of circumferential convective heat transfer, though it does not significantly changed measurement bias.

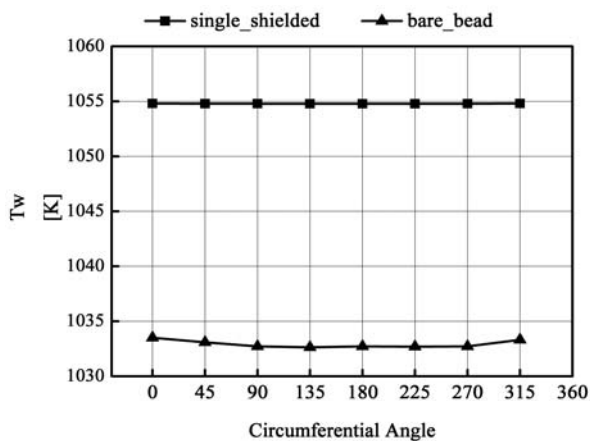


Fig. 14 The surface average temperature versus circumferential angle.

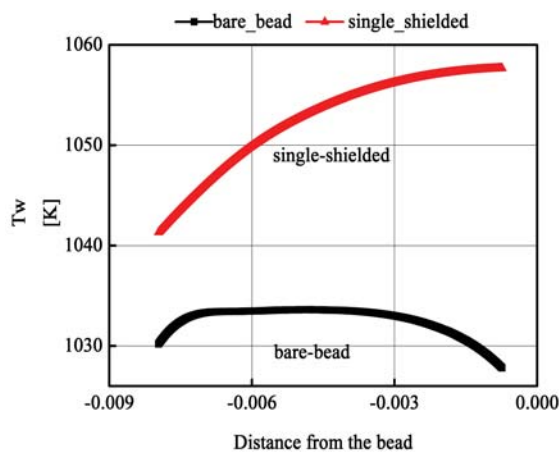
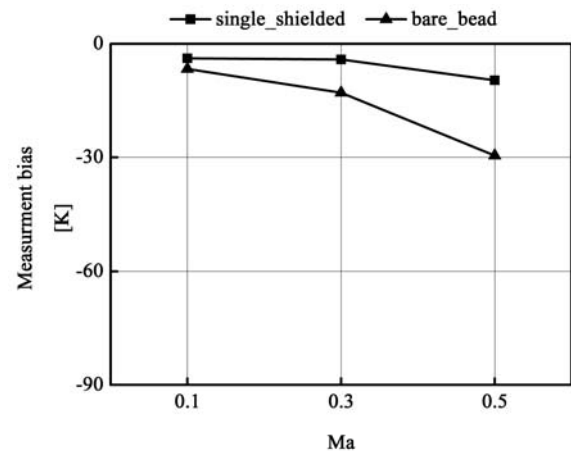


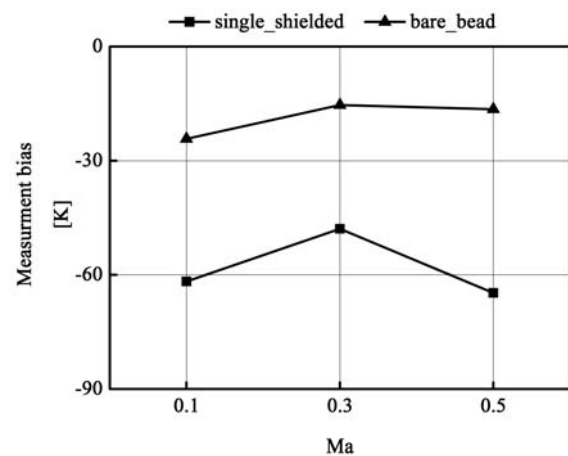
Fig. 15 The surface average temperature versus distance from the bead

Effect of shield on thermocouple temperature measurement bias

As for the measurement bias, it can be characterized using the difference between the incoming airflow total temperature (T_t) and the representative thermocouple



(a)



(b)

Fig. 16 Temperature measurement bias of two type thermocouple versus Ma: a) T_w 293 K; b) T_w 1000 K.

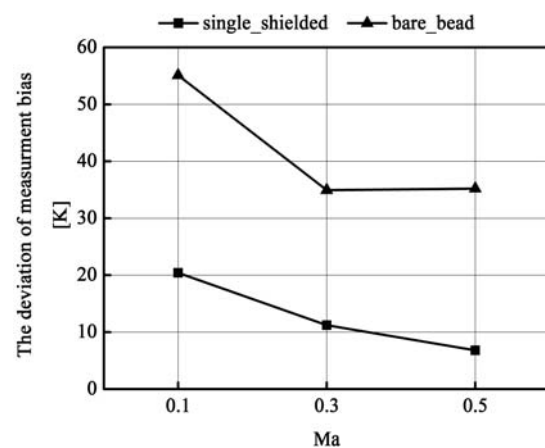


Fig. 17 Variation of temperature measurement bias caused by two different wall temperature (293K,1000K) versus Ma

temperature (T_b) in this paper. The representative thermocouple temperature here

(T_b) was calculated by using a bead volume-weighted average temperature as follows:

$$T_b = \frac{1}{V_b} \int T \cdot dV = \frac{1}{V_b} \sum_{i=1}^N T_{b,i} \cdot dV_i \quad (4)$$

It is worthwhile reminding that the main objective of this study is to illustrate the difference of the bare-bead and the single-shielded thermocouples in temperature measurement and to attempt to estimate the relative magnitude of the temperature measurement bias in steady state rather than delivering an exactly absolute value of the thermocouple temperature measurement bias.

From Fig.16 the shield does not change the variation trend of temperature bias with increasing Mach numbers in the subsonic region.

From Fig.16.a), the temperature measurement bias of two types of thermocouples increases with increasing Mach numbers when the wall temperature (T_w) is close to the airflow total temperature (T_t). It is mainly due to the velocity error is proportional to airflow velocity.

However, it can be seen from Fig.16.b) that the relationship of temperature measurement bias and Mach number is not monotonous when the wall temperature is far less than the airflow total temperature. There is an optimum Mach number at which point the temperature measurement bias is the minimum. It is mainly due to the radiation loss cannot be neglected when the wall temperature is low, and the radiation effect decreases with increasing Mach number.

The shield effectively reduces the temperature measurement bias and reduces the effect of wall temperature on the temperature measurement bias as compared to the bare-bead thermocouple. Fig.17 shows the deviation of the temperature measurement bias when the wall temperature changes from 293 K to 1000 K at different Mach number. The maximum

deviation caused by varied wall temperature, appears when Ma is 0.1, decreases from 55 K to 20 K as the existence of the shield.

The shield effectively reduces the influence of flow velocity on the temperature measurement bias as compared to the bare-bead thermocouple as well. It can be seen from Fig.16 that when the wall temperature is 1000 K the deviation of the single-shielded thermocouple temperature measurement bias is 5 K with the Mach number changes, which is 15 K less than that of the bare-bead thermocouple.

Conclusion

Two kinds of thermocouple temperature measurements in hot, flowing air are simulated respectively by means of CFD. In order to compare with the experimental results, a cylindrical computational domain is established, which is the same size with the hot calibration wind-tunnel. The computational domain wall representing the surrounding in the real thermocouple measurement exchanges radiative heat with the thermocouples. All the simulations are performed using a commercial flow solver (Fluent), using a hybrid mesh, Reynolds-averaged transport equations, Realizable κ - ϵ turbulence model and radiation model (DO). A combined solution of the flow field, energy equations, conduction in the thermocouple and radiation between different surfaces is obtained in these simulations.

The parameters varied in two kinds of thermocouple thermal simulations are the airflow Mach number (from 0.1 to 0.5) and the computational domain wall temperature (from 293 K to 1000 K) when the airflow total temperature is fixed to 1073 K. The effect of shield on temperature distribution and temperature measurement bias are discussed, and the results show that:

(1) The numerical method of fluid-solid conjugated heat transfer is a feasible approach

for studying the temperature measurement using a thermocouple.

(2) The existence of the shield can be expected to reduce the temperature measurement bias both by improving bead surface temperature and by reducing bead surface temperature gradient.

(3) The existence of the shield reduces surface heat flux and changes the direction of wires inner heat conduction when the wall temperature is low.

(4) The shield effectively reduces the effect of wall temperature on the temperature measurement bias.

(5) The shield effectively reduces the influence of air-flow velocity on the temperature measurement bias.

Acknowledgement

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